Development of an Ultra Lean Burn Natural Gas Engine

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ARES Program Goals

- ✓ **High Efficiency** – Fuel-to-electricity conversion efficiency of at least 50%.

- ✓ **Environmental Superiority** – NOx < 0.1 g/hp-hr (natural gas).

- **Reduced Cost of Power** – Energy costs, including O&M, at least 10% less than current state-of-the-art engines.

- **Fuel Flexibility** – Adaptable to future firing with dual fuel capabilities, include further adaptation to hydrogen.

- **Reliability and Maintainability** – Equivalent to current state-of-the-art engines.

Lean burn fueling yields simultaneous benefits of increased efficiency and decreased emissions with lean air-fuel mixtures
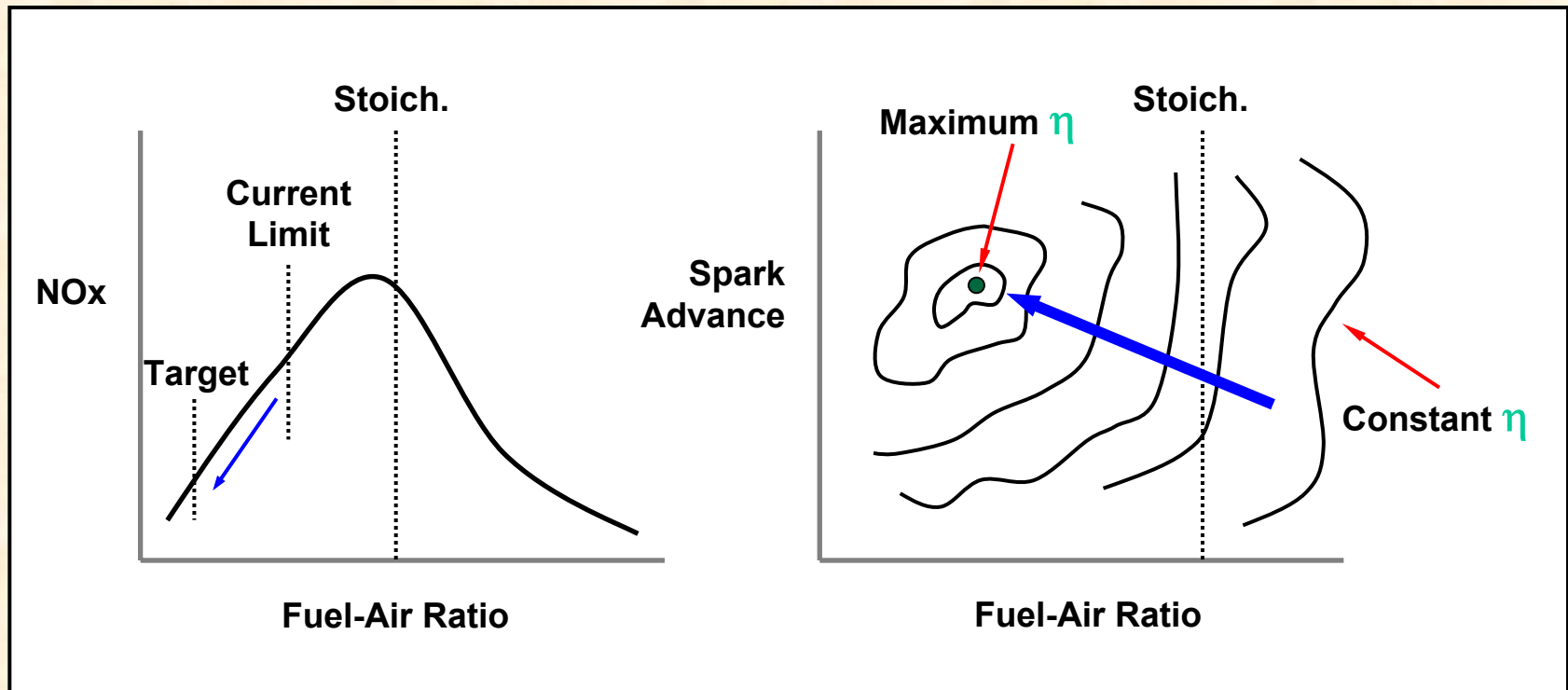
Ultra lean burn strategy currently has three tasks

- **Integration of technologies and lean characterization.**

- **Hydrogen addition via simulated reformer.**

- **New ignition technology.**

- ***Aftertreatment (if further emissions reduction required).***

Related/complimentary new project in FY 2002

    Adaptive nonlinear control.

New technologies are being developed on a small natural gas (NG) Kohler engine

- **NG Kohler Command 25**

- **Available in 9.5 kW generator set (size for single family residence).**

- **Scale up of technologies necessary to prototypical size.**

# Majority of development on small engine dynamometer

- **Electronic governor on generator set not robust enough for technology development.**

- **Dynamometer setup necessary for precise speed and load control.**

- **Optimized technologies will be demonstrated on generator set.**

Kohler engine installed on dynamometer – instrumented for performance measurements

- Air and fuel rates.
- Current and voltage (generator set only).
- In-cylinder pressure.
- Emissions.
- Air/fuel ratio.
- Temperatures and pressures.
- Crank shaft encoder.
- High and low speed DAQ systems.

Generator set performance has been baselined (3600 rpm)
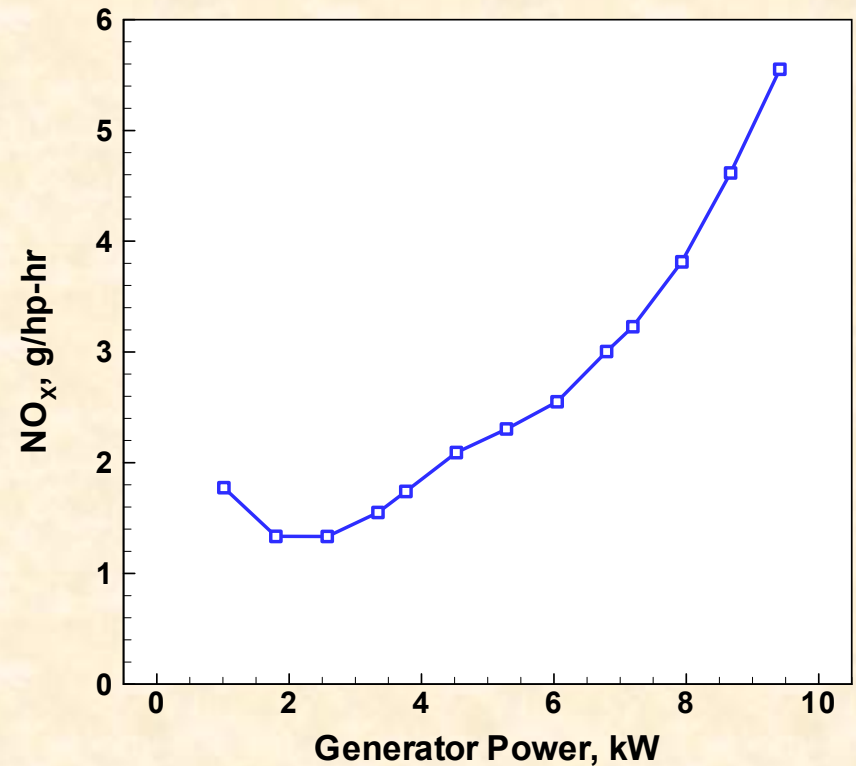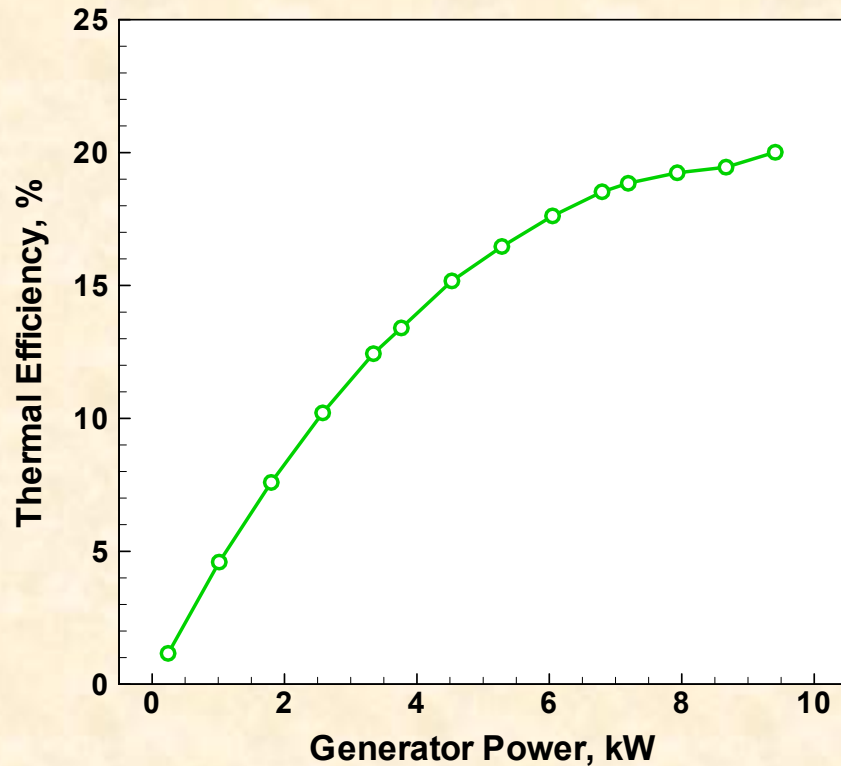
Fueling System Modifications

- **Kohler fueling system:**
  - **significant cyclic variations in mixing,**
  - **non-uniform distribution between cylinders,**
  - **increased cyclic combustion variations.**

- **Fueling system was replaced with port fuel injectors for more precise control.**

Status of setup and lean characterization

- **Laboratory was recently moved to a new facility.**
- **Dynamometer setup and generator set are instrumented and commissioned.**
- **Generator set has been characterized to provide benchmark for future experiments.**
- **Lean burn characterization is in progress.**

Deliverables

- ✓ **Baseline generator set (June 2001)**
- **Characterize engine under lean burn conditions (June 2002)**

Hydrogen addition extends the effective lean combustion limit

- **Previous experiments demonstrate extension in stable lean limit as well as significant reduction in NO_x emissions.**

- **Generation of reformate gas by partial oxidation is demonstrated technology and produces H_2, CO, and N_2 from CH_4.**

- **Integration of reformer into control system is feasible (beyond scope of this project).**

Experiments on a gasoline fueled SI engine illustrate the benefits of hydrogen addition
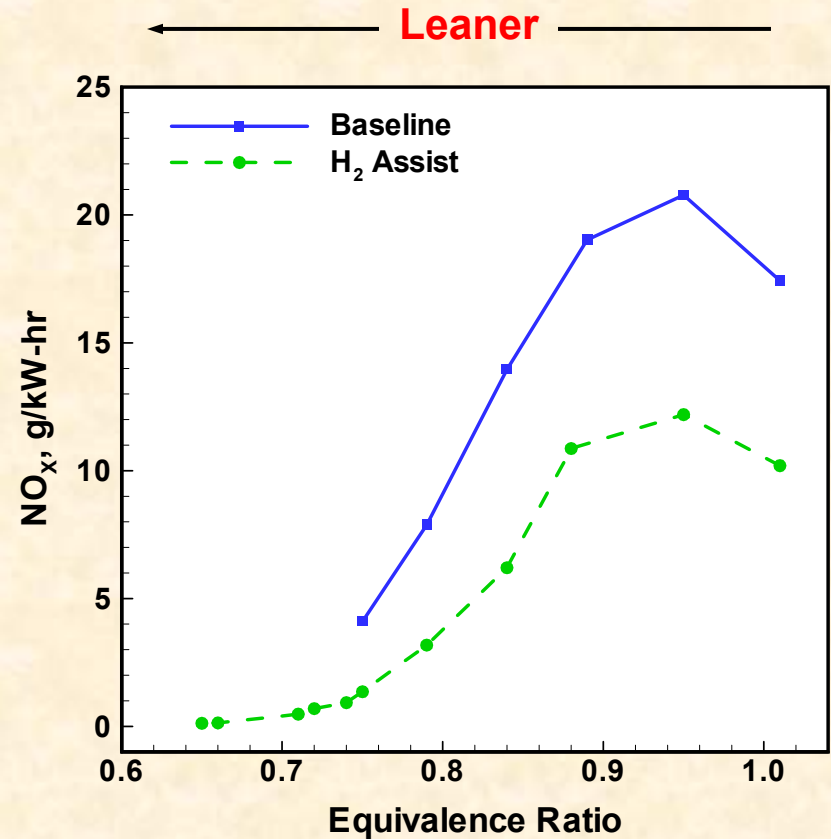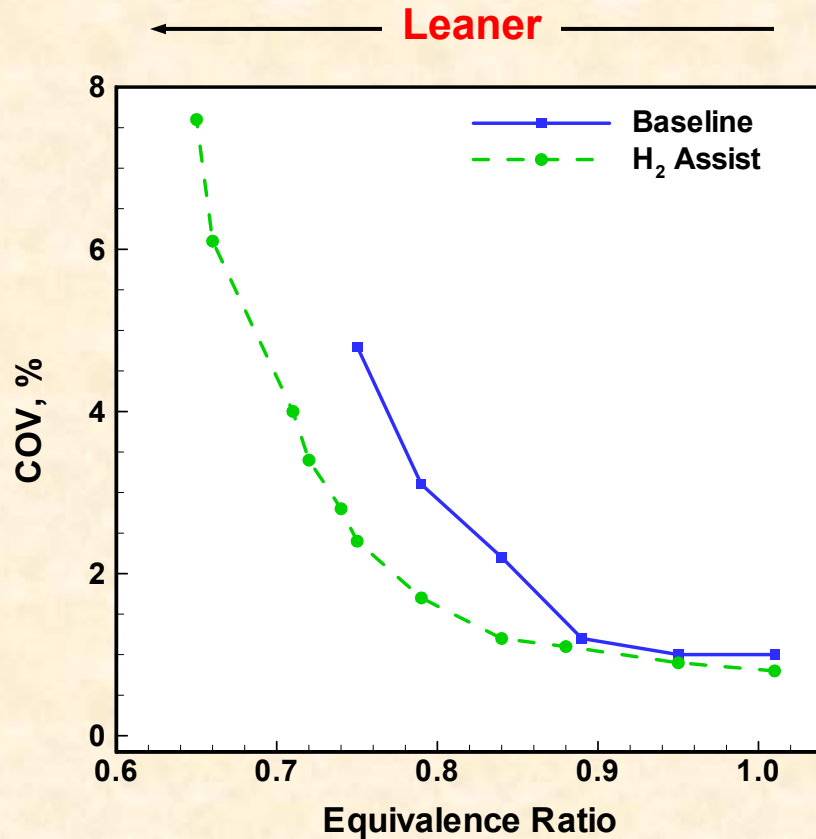
Status of Hydrogen Addition Task

- **Contacts made with fuel cell industry to determine best mix of H_2 and CO to simulate NG reformate.**
- **High-capacity mass flow controllers have been configured to deliver the simulated reformate to the intake.**
- **Gas mixtures and necessary equipment have been finalized for this task.**

Deliverables

- **Characterize engine with hydrogen addition under lean conditions (September 2002)**
- **Demonstrate lean burn with hydrogen addition and RASP (June 2003)**

New ignition technology will improve probability of combustion under lean conditions
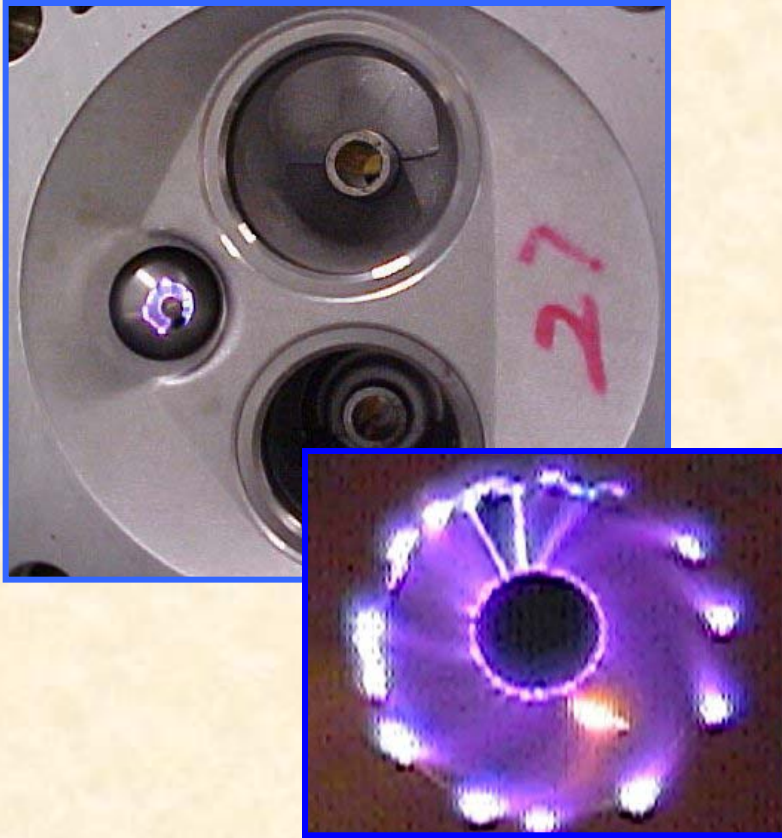
- **Rotating Arc Spark Plug (RASP)** has broader spark and multiplicity of discharges.

- Magnetic field at plug tip causes spark to rotate.

- Durability experiments being performed with generator set.

- Engine experiments have provided valuable information for design improvements.

RASP refinement is ongoing

- **High temperatures in the engine caused some degradation of the RASP magnet.**

- **RASP housing has been re-designed to improve heat transfer to the surroundings.**

RASP housing has been re-designed to lower magnet exposure temperature

Original Design

Modified

Status of Rotating Arc Spark Plug (RASP)

- Demonstrated on bench scale.
- Installed and evaluated for durability on one cylinder of generator set.
- In-engine development ongoing.

Deliverables

- ✓ Ignition system bench scale development (December 2001)
- Characterize engine with RASP (December 2002)
- Demonstrate lean burn with hydrogen addition and RASP (June 2003)

Collaborations/Interactions with Others

- **Project is pre-competitive (no formal collaborations or subcontracts with industry or academia).**

- **Related projects are collaborative with multiple sponsors.**

  - **Ignition** – New spark plug developed with ORNL internal funds. Ignition R&D funded by OTT with industry interaction.

  - **H2 Addition** – Interactions with academia and industry.

  - **Aftertreatment** – Interaction with academia and industry. Related projects sponsored by OTT.

- **Heavily involved with multiple sponsors, states, industry, and academia.**

Summary

- **Project is progressing well. On target to meet future deliverables.**

- **Laboratory has been relocated to new facility and setups have been commissioned.**

- **Lean characterization in progress.**

- **RASP engine evaluations are ongoing and have led to design modifications.**

- **Reformer simulation gases and hardware are in place. Characterization will commence after lean burn optimization.**

Other Relevant Issues to Lean Combustion and Meeting ARES Goals

- **Predictive feedback control for extending the stable lean combustion limit (funded FY 2002).**

- **Scale up previously discussed technologies to engine size of interest (Caterpillar G3406).**

- **NG/Reformate composition and control feedback.**

- **NOx storage and reduction.**

- **Systems analysis of generator set.**

Nonlinear Control of Cyclic Dispersion in an Ultra Lean Burn Spark Ignition Engine

(New Project FY 2002)

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Project Goals

- **Further improvements in fuel efficiency and NOx emissions through predictive feedback control.**

- **Extend the effective lean limit.**

- **Improve robustness of ultra lean burn operation by eliminating undesirable combustion events before they occur.**

Predictive control development and implementation has three tasks

- **Hardware development for evaluating control algorithms on a natural gas (NG) engine.**

- **Model based control algorithm development and refinement.**

- **Engine based control algorithm implementation.**

Cycle-to-cycle engine dynamics are very complicated under extreme lean conditions
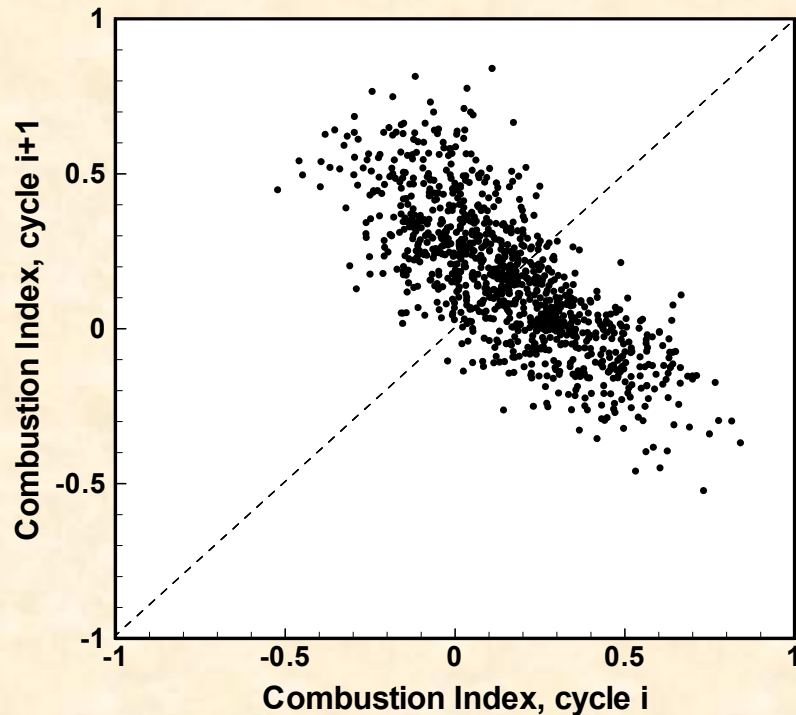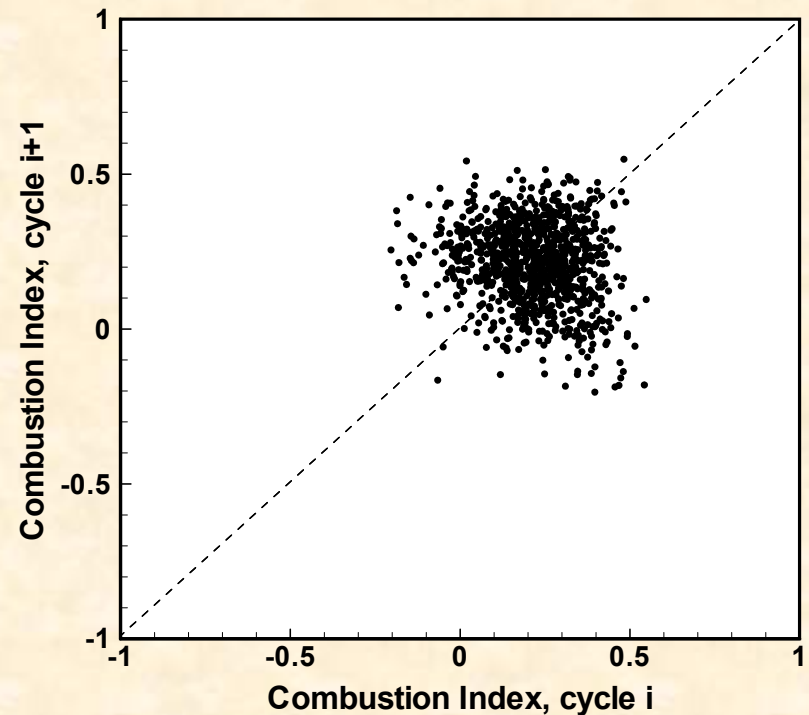
(single-cylinder gasoline engine)
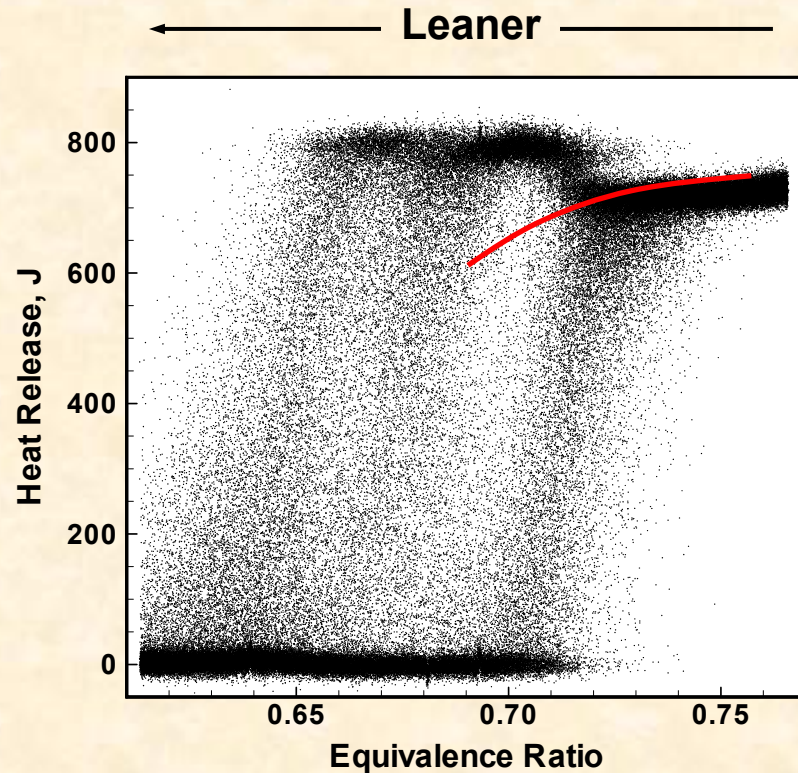
Experimental Data

Map Reconstruction

**Targeted Control Region
Shown in Red**

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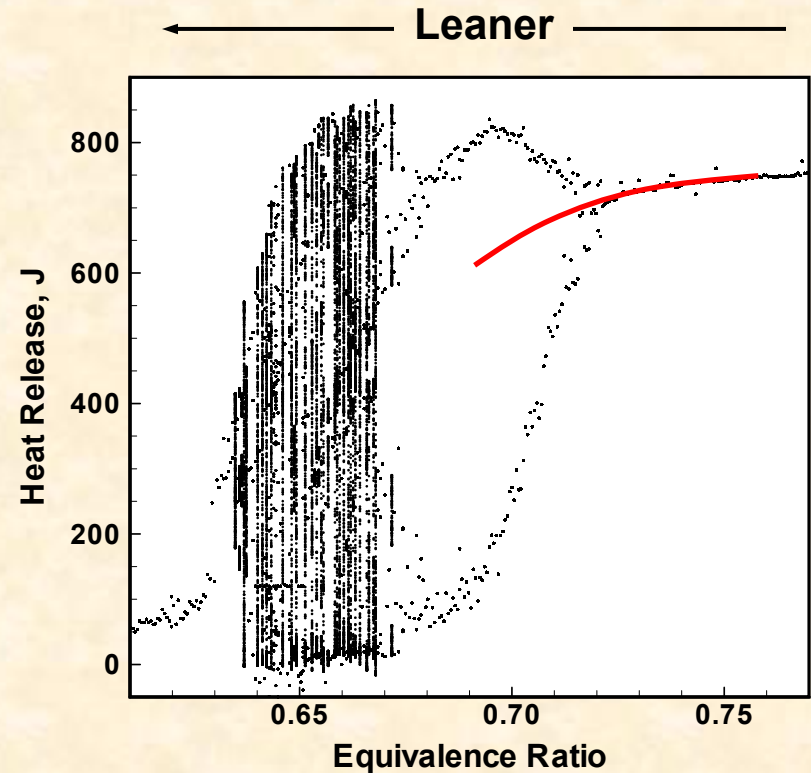
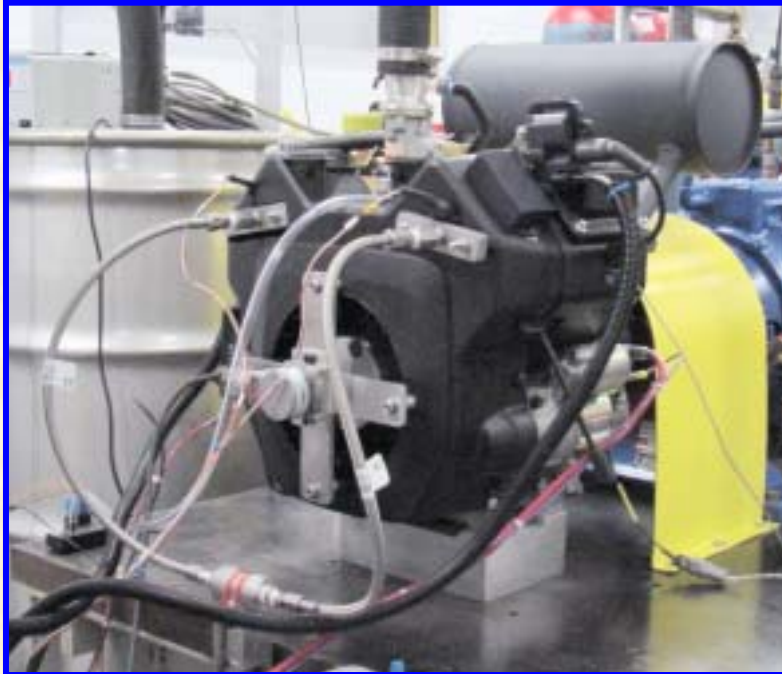# Nonlinear control of lean operation by ORNL and Ford Motor Company

Uncontrolled

Controlled

Control system will be developed and implemented on small Kohler NG engine

- **NG Kohler Command 25**

- **Same engine used for ARES ultra lean burn project.**

- **Scale up of technologies necessary to prototypical size.**

Engine Hardware Control System

- **System must be:**
  - flexible allowing for the easy implementation of adaptive control algorithms.
  - high speed allowing for cycle-to-cycle perturbations in ignition timing and fueling parameters.

- **Possible feedback parameters include in-cylinder pressure, crank shaft acceleration, etc.**

Status of hardware development

- **Possible hardware/software configurations are being evaluated.**
- **Hardware will most likely be "real-time" type board(s).**
- **Software package will be visual based for easier user interaction (e.g., Visual Basic, Nl Labview).**
- **May require two computers for processing of data and perturbing control parameters.**

Deliverable

- **Develop nonlinear control system hardware (December 2002)**

Control Algorithm Development and Refinement

Control strategies make use of the deterministic component of combustion oscillations to predict undesirable combustion events and to prevent them by perturbing control parameters.

- **Symbolization**

    Combustion measurements converted to small set of discrete values for efficient real-time analysis of predictable patterns.

- **Map Reconstruction**

    Low order maps of combustion measurements provide explicit predictions of future events.

Control algorithms predict and prevent undesirable combustion events

- "Library" or "moving window" provides history information.

- Perturbs equivalence ratio based on

  - current combustion state (where we are)

  - symbol or map based history (where we have been).

  - period-one fixed point (where we want to be).

- Exponentially weighted moving average (EWMA) filter maintains nominal equivalence ratio.
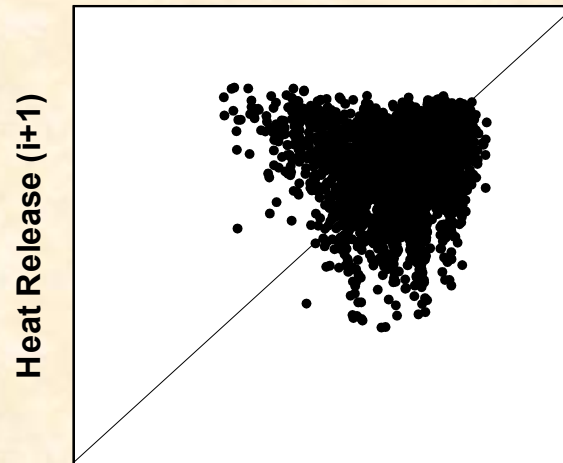
Example control results from model simulation
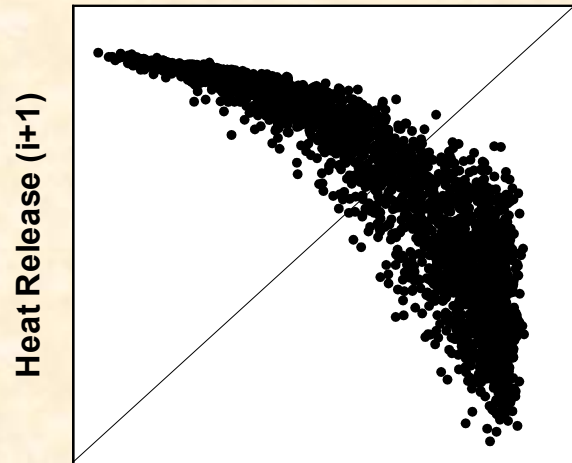
No Control
COV = 36%
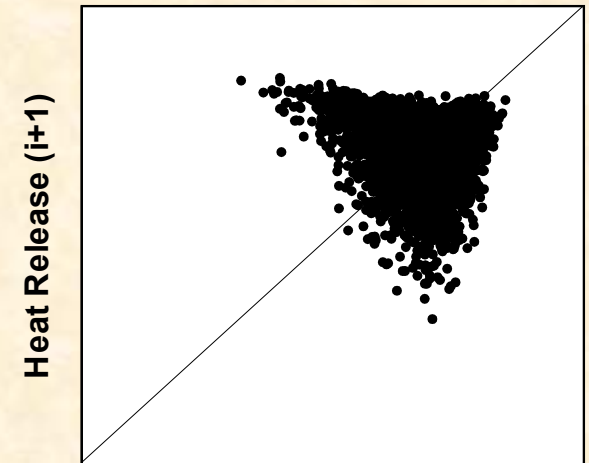
Symbol-Based
COV = 13%

Map-Based
COV = 11%

Nominal equivalence ratio was maintained (i.e., no fueling increase).

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Status of predictive control algorithm development and implementation

- **Model development of algorithms in progress.**
- **Recent results indicate symbol- and/or map-based techniques show promise.**
- **Engine implementation will begin after hardware is developed.**

Deliverable

Demonstrate nonlinear control under ultra lean conditions on an engine (December 2003)

Collaborations/Interactions with Others

- **Project is pre-competitive (no formal collaborations or subcontracts with industry or academia).**

- **Related projects are collaborative with multiple sponsors.**

    - *Nonlinear Control* **– Interactions with academia and industry. Related project sponsored by OTT.**

    - *Fast Acting NG Valve for Control* **– Collaboration with industry and New York state.**

- **Heavily involved with multiple sponsors, states, industry, and academia.**

Summary

- **Project is progressing well.**

- **Kohler engine setup developed for existing ARES program is being used for this investigation.**

- **Hardware development planning is underway.**

- **Symbol- and map-based control algorithms show promise based on model evaluations.**